A SEMI-AIRBORNE EM STUDY OF THE HOPE ORE DEPOSIT (NAMIBIA) USING A DRONE-BASED CONCEPT

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Summary

Unmanned aerial vehicles (UAVs) are ideally suited as carriers for passive receiver instruments. To demonstrate the capability of UAVs for semi-airborne electromagnetic (EM) application, we have conducted a drone-based semi-airborne EM survey at the Hope ore body (Namibia), a well-explored volcanogenic massive sulfide deposit. The conductive deposit is embedded in a resistive sediment and is a perfect case study target for methods that are sensitive to electrical conductivity. The semi-airborne method differs from conventional airborne EM methods by the installation of powerful ground-based transmitters facilitating greater penetration depths. By determining magnetic transfer functions and estimating 2D subsurface conductivity models on that basis, we aim to image the characteristics of the deposit.

We have determined consistent transfer functions up to 2km distance to the employed transmitters at frequencies ranging from 32Hz to 4kHz. However, there remain challenges such as UAV-related EM noise limiting the data quality. It was possible to estimate conclusive inversion models, map the extent of the conductive target successfully, and track down the ore body to a depth of more than 300m. It is yet unclear to which depth the Hope deposit can be resolved — this would require an extension of the survey.

A semi-airborne EM study of the Hope ore deposit (Namibia) using a drone-based concept

Introduction

Semi-airborne electromagnetics (EM) utilizes powerful ground-based transmitters and a passive airborne receiver towed by an aircraft to detect conductive targets in the subsurface. In comparison with conventional airborne EM methods larger penetration depths can be achieved (Steuer et al., 2020). Moreover, the transmitter geometry can be adjusted to the particular target of interest in order to maximize the inductive response of the target.
In recent years, several implementations of the semi-airborne EM method on unmanned aerial vehicles (UAVs) have been presented (Wu et al., 2019; Smit et al., 2022). UAVs are cost-effective and have beneficial flying capabilities, but they are limited in payload and flight duration. Without the necessity to carry heavy transmitter payloads, the semi-airborne EM configuration is ideally suited for UAVs.
We present the results of an extended multicopter semi-airborne EM case study to characterize the Hope ore body (Namibia). Measurements employed multiple electric dipole transmitters on the ground and both induction coil and total magnetic field airborne receivers. Here, we focus on induction coil data. The UAV setup and the methodology follow the approach described in Kotowski et al. (2022) and the principles as laid out in Becken et al. (2020).
The Hope ore body, a part of the Matchless Belt cluster in Namibia (Killick, 2000) is a well-explored volcanogenic massive sulfide deposit providing perfect conditions for a drone-based study. A substantial copper concentration makes this deposit a very good electrical conductor, embedded in a resistive sediment. The tube-shaped ore body has a diameter of about 100 m and submerges to more than 300 m depth. Due to several drillings, the extent and location of the deposit are well known.

Method and survey setup

The semi-airborne EM method is sensitive to electrical conductivity. Strategy of the method is to map the induced EM response excited by a time-varying electric current. In the frequency domain, a linear relation between the injected current amperage $I(\omega)$ and the observed magnetic flux density $\mathbf{B}(\mathbf{r},\omega)$ can be stated:

$$\mathbf{B}(\mathbf{r},\omega) = \mathbf{T}(\mathbf{r},\omega) \cdot I(\omega)$$

Here, $\mathbf{r}$ denotes a point in space and ω denotes the angular frequency. The magnetic transfer function $\mathbf{T}(\mathbf{r},\omega)$ contains information about the subsurface conductivity distribution and can be determined via a regression. Conductivity models can be derived using controlled-source EM inversion codes.
In the survey area, four horizontal electric dipole (HED) transmitters of a length of 2 km each and a spacing of about 1 km to each other were deployed (Fig. 1). These transmitters were operated individually and their footprint was surveyed throughout multiple overlapping flight patches. One patch covers an area of about 1 km^2 and per transmitter six to twelve patches were completed. The survey covers an area of about 11 km^2.
We injected a 100% duty cycle square wave current of up to 8 A and a 32 Hz base frequency current was injected while flying with the coil receiver (32 kHz sampling rate). To ensure the attitude information of the coil triple during flight, an inertial measurement unit (IMU) was employed. We applied a short-time Fourier Transform to current clamp recordings and magnetometer data and calculated magnetic transfer functions via a least squares regression for logarithmically equidistantly binned frequencies. To weight

the data an estimation error resulting from the regression, an absolute error (noise floor) on amplitude (0.5 pT/A) and phase (10°) and a relative amplitude error (10%) were taken into account.

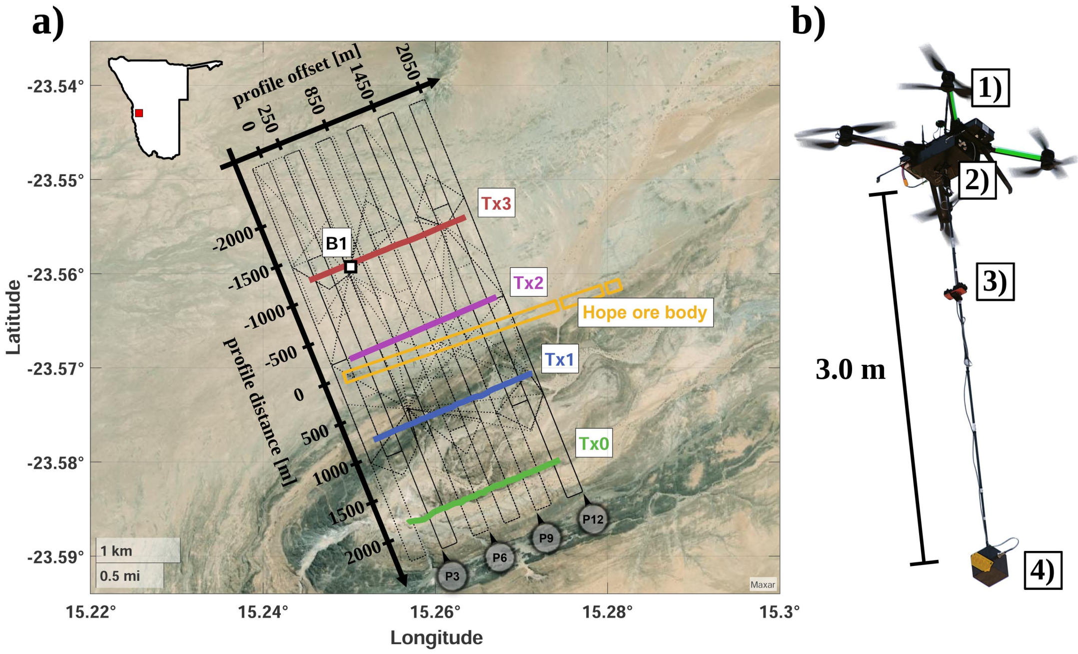

Figure 1 *Survey site map (**a**) at the Hope deposit (Namibia) and employed UAV (**b**) equipped with an induction coil receiver. Mapped are the installed transmitters (Tx0, Tx1, Tx2, Tx3), the flight paths (black dotted lines), and four profile lines (P3, P6, P9, P12). A magnetotelluric site (B1) was deployed as a reference. The Hope ore body (yellow) plunges in northeast direction. The aircraft system is composed of an Aerialis X825 octocopter (1), a Metronix ADU08 24/32-Bit logger (2), a Xsens MTi-G-710 IMU or iPhone (3) and a Metronix SHFT-02e induction coil triple (4).*

Results

We have estimated 2D conductivity models for multiple profile lines (Fig. 2), which are composed of individual flight patches. MARE2DEM (Key, 2016), a 2D controlled source EM inversion code based on an adaptive finite element algorithm was used for this purpose. Here, we included the horizontal and the vertical transfer function components perpendicular to the HEDs. 16 base-ten frequency bins ranging from 32 Hz to 4 kHz were considered for inversion. Data points close to the active transmitter (< 250 m) and points with a distance of more than 2 km were excluded. In addition, inconsistent data points or data with poor signal-to-noise ratio were masked manually. In Figure 3 vertical transfer function estimates along a single profile (P9) are shown. The model response of the final inversion result is also depicted. The model domain has been parameterized with triangles which increase in size with depth (20 m triangle side-length at the surface). An initial model, which takes into account the local topography, has a bounding box of 200×200 km^2 and a homogeneous resistivity of 100 Ωm.
Transfer functions have typical characteristics with respect to the EM source. Near the HED transmitter, the field is dominated by the primary field and geometrical decay. With increasing distance and frequency, inductive effects become more important. The vertical component switches sign across the transmitter where the horizontal components have a maximum.
The estimates in Figure 3 exhibit these characteristics. A deviation in symmetry regarding the transfer function flanks suggests inhomogeneities in subsurface resistivity. Such an asymmetry in amplitude is evident for transmitter Tx1, Tx2, and Tx3. At the location of the Hope ore body, estimates at frequencies above 500 Hz related to Tx1 decrease significantly. Noted can be also prominent features in the behavior of the phase. Phases at frequencies greater than 200 Hz related to Tx3 are strongly affected by the presence of the deposit. There are further features such as the Tx2 amplitude decay at -600 m profile distance at high frequency and the Tx1 phase course at 2200 m which are not directly related to

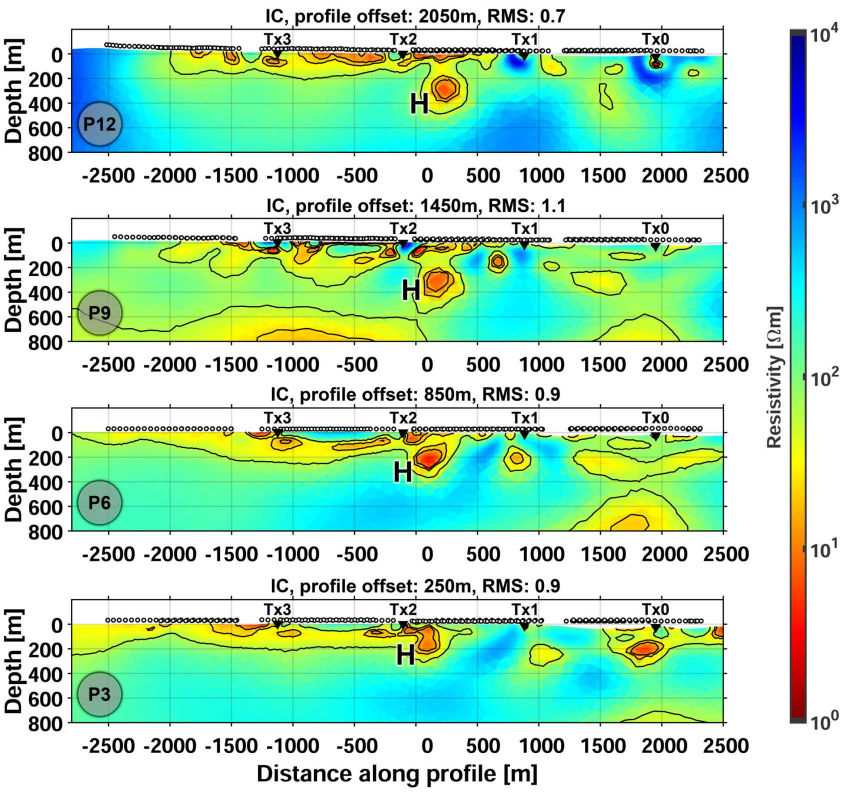

Figure 2 *2D inversion models based on the induction coil triple recordings. Resistivity models were estimated along profile lines (P3, P6, P9, P12) across the conductive Hope ore body (H) using MARE2DEM.*

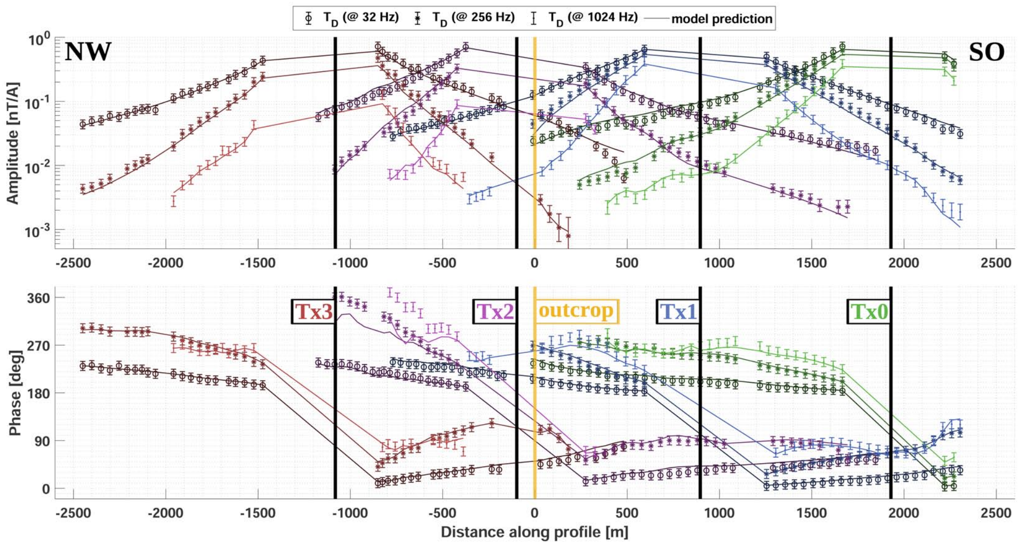

Figure 3 *Transfer function estimates along a profile line (P9). Depicted are estimates of the vertical component (T_D) for three binned frequencies (32 Hz: circles, 256 Hz: stars, 1024 Hz: dots) depending on the active transmitter (Tx0: green, Tx1: blue, Tx2: magenta, Tx3: red). Shown are also respective model responses (solid lines). The complex-valued transfer functions are expressed by an amplitude and a phase.*

the ore body. However, the transfer function estimates are very consistent for frequencies up to 4 kHz and up to a distance of 2 km to the active transmitter.

The four inverted 2D resistivity sections, shown in Figure 2, reveal a prominent conductive anomaly ($< 20\ \Omega m$) located centrally beneath the profiles. It is centered at 200 m to 400 m depth and plunges

from the southwest profile (P3) eastward (P12). We identify this anomaly with the Hope ore body. Size, position and resistivity of the body are consistent with the information available on the boreholes and previous geophysical ground studies.
The models indicate also conductive near-surface layers disconnected by a resistive bulk beneath transmitter Tx1 and some conductive features northwest of the Hope deposit and below Tx0. Whether less prominent structures are real geological features is not certain. Artifacts may be caused by systematic data errors (e.g. impreciseness in the reorientation of coil data into earth-fixed coordinates, current clamp or induction coil calibration inaccuracies), multicopter-related EM noise affecting data quality, or numerical problems near the transmitters. However, the forward responses of the final inversions match the estimated transfer functions (cf. Fig. 3). Apart from discrepancies at Profile P9 for data related to Tx2 at -800 m profile distance, the model provides a result that is capable to explain the observations very well.

Conclusion

The study of the Hope deposit (Namibia) demonstrates the capability of the drone-based semi-airborne EM technique. It was possible to map the extent of the conductive target successfully and to track down the ore body to a depth of more than 300 m. The topography conditions in the survey area are suited for inversion on a 2D basis and the resulting model responses match our observations well. However, there remain limitations such as EM noise from the UAV or sensor inaccuracies that restrict the data quality. Therefore, it is of great importance to carefully consider the geometry of the individual transmitters and the arrangement of the flight patches prior to a survey. It is yet unclear to which depth the Hope deposit can be resolved — this would require an extension of the survey area to the east.

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